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High-Voltage Lifetime Function of the PZT Ceramic/Gas Insulator Interface in Underwater Sound Transducers

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The high-voltage endurance function of PZT ceramic in air and some other insulator gases, including sulfur hexafluoride, is described and an empirical equation is presented for computing the lifetime to failure. The effects of water vapor contamination, gas pressure, and ceramic thickness on the endurance function are reported. Details of the mechanism leading to electrical failure are discussed and application of these findings to sonar transducer specifications and reliability evaluation is indicated.

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HIGH-VOLTAGE LIFETIME FUNCTION OF THE
PZT CERAMIC/GAS INSULATOR INTERFACE IN
UNDERWATER SOUND TRANSDUCERS

INTRODUCTION

Electrical breakdown is a basic failure mode of high-power
sonar transducers. It is not the only, or necessarily the pre-
dominating, failure mode but occurs often enough that it consti-
tutes a substantial repair and replacement problem in sonar
arrays. Many of the factors accompanying electrical failure are
random processes associated with electrical stress events that
momentarily exceed the strength of the insulation system. There
are, however, other electrical processes (such as corona dis-
charges) that gradually reduce the dielectric strength of solid
materials [1] and result in a time-dependent failure mode.

Electrically polarized lead-zirconate-titanate (PZT) ceramic
discs are the active elements and one of the main insulating
materials in sonar transducers. While tests have shown [2] that
PZT ceramic has a dielectric strength on the order of 3900 kV/m
(100 V/mil), this exceeds by a factor of 10 the operating level of
275-390 kV/m (7-10 V/mil) maximum that experience indicates for
reliable transducer design. The mechanism of failure at higher
voltage levels appears to be electrical degradation of the
solid/gas interface that progresses to eventual surface flash-
over.

Previous studies [3,4] have documented the problems of
electric corona and flashover in sonar transducers. These
investigations include subjects such as silver migration, rough
electrode edges, lacquer and resin coatings, various insulating
gases, water condensation, and parallel insulation mathematical
modeling. The reports implicate electrical corona as a factor
leading to transducer failure, but the data presented are unre-
lated to the corona phenomena. Suggestions of other electrical
failure mechanisms are omitted.

Another study [5], a part of the Sonar Transducer Reliability
Improvement Program (STRIP), indicates that *creepage* or surface
flash-over of PZT ceramic is an electrical failure mode in trans-
ducers. The results are for an electrode configuration used in
3-1 mode transducers and apply to a short-time high-voltage
exposure. The report indicates that sulfur hexafluoride (SF_6) and

the perfluorocarbon gases (C_2F_6, C_3F_8, and C_4F_{10}) are initially superior to nitrogen (N_2) and air for use in sonar transducers, but reference to time-dependent failure mechanism is absent.

EXPERIMENTAL TECHNIQUE

The purpose of the tests reported here was to demonstrate the time-dependent factors associated with electrical failure of sonar transducers. The simplified transducer drawing of Fig. 1 shows the surface flashover paths where failure normally happens. The voltage endurance fuction developed by these measurements describes the dependence of dielectric strength on the time of exposure to high voltage. The first step in the process was to measure the breakdown voltage by increasing the drive voltage across ceramic piece-parts at a rate of about 100 V/sec. After this, a specific lower drive voltage was applied to a new test specimen and the time to the failure event was measured. The second step was repeated using various drive voltage levels until the endurance function curve was completed. The failure event was clearly indicated by electrical arcing between the test specimen electrodes. Arcing in a sonar transducer permanently reduces the dielectric strength and qualifies as a unit failure.
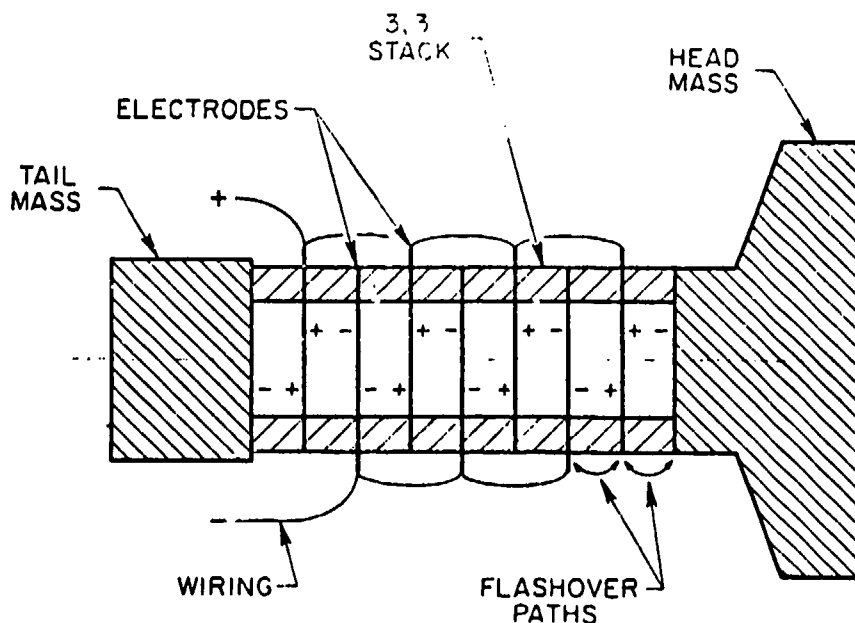

Fig. 1 - Surface flashover paths in 3,3 mode sonar transducers

Test Apparatus

Figure 2 shows the high-voltage test cell and mounting of the PZT test specimen. The 2000-ml glass chamber was sealed with O-rings so that a vacuum could be pulled before back-filling with gas. The spring loop provided pressure contact to the test specimen electrodes, thus avoiding the need to make solder connections. To avoid external corona, all electrical leads associated with the high-voltage terminal were made as large as practical with edges rounded; for instance, the main lead was of 1.27-cm (0.5-in.) diam copper tubing.
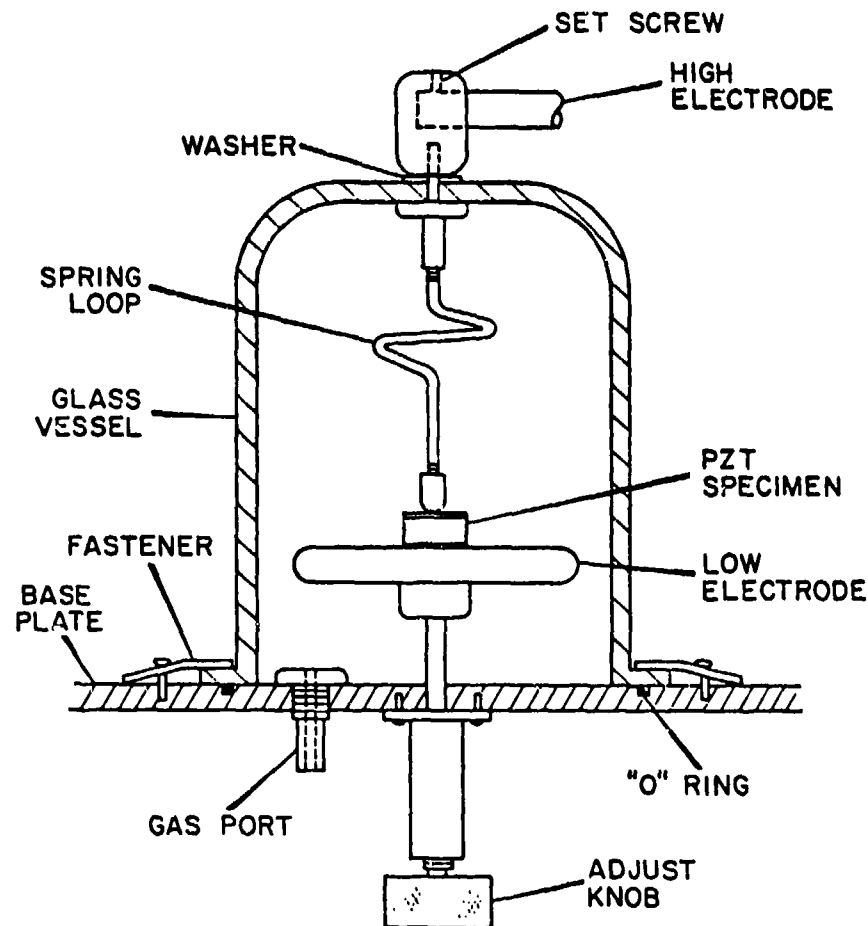

Fig. 2 - Sketch of high-voltage test cell

A block diagram of the test system is shown in Fig. 3. This was a partial discharge test equipment (J.G. Biddle Co. System No. 662045-01) that used ASTM Standard Method D1868-73 to measure corona [6]. The ×1000 attenuator probe and digital voltmeter were added to improve the measurement of test voltage readout and were calibrated using instruments with accuracy traceable to NBS. The current transformer with amplifier and oscilloscope was used to measure the electrical current waveform associated with the test specimen. A timer was instrumented with the system to record time-to-failure. For the purpose of safety, all high-voltage equipment was enclosed in a steel cabinet with interlock switches to disconnect power when the access door was open.
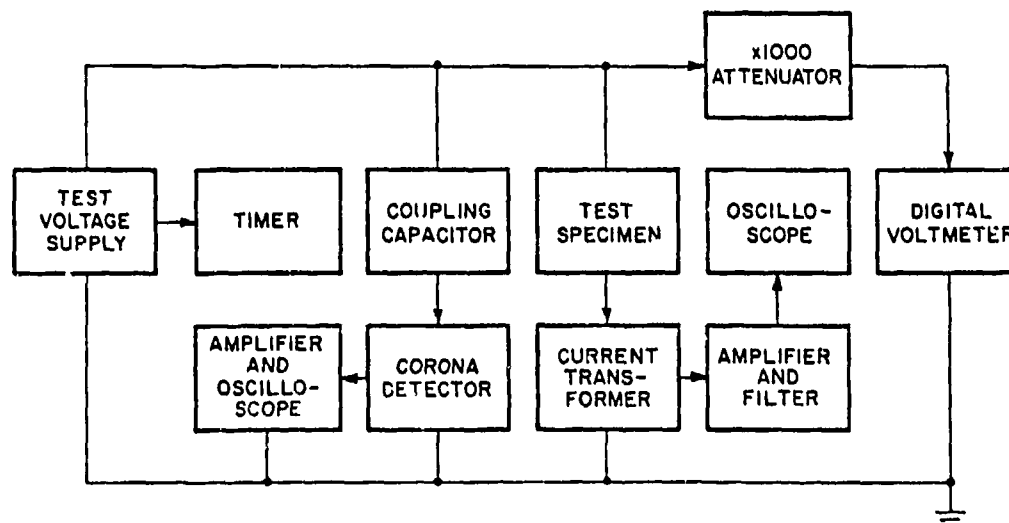
Fig. 3 — Test system block diagram

Test Specimen Conditioning

The quality-control factors of the test specimens were made as uniform as possible to obtain reproducible results. The PZT ceramic type was Gulton HDT-31 discs with 0.635-cm (0.25-in.) or 1.27-cm (0.5-in.) thickness and 2.54-cm(1-in.) diam. The specimens were thoroughly cleaned, inspected for visible flaws, and dried at 60°C for 40 hours. They were then stored in a desiccator until used.

Insulator Gas Selection and Control

The insulator gases chosen for these tests were sulfur hexafluoride (SF$_6$), perfluoroethane (C$_2$F$_6$), perfluoropropane (C$_3$F$_8$), air, and nitrogen (N$_2$). The similarities and differences in this series of gases are intended to aid the analysis of the endurance function. Ranked in the order of their descending electrical strength they are: C$_3$F$_8$, SF$_6$, C$_2$F$_6$, air, and N$_2$. Air is stronger than nitrogen due to the electron attaching action of the oxygen component [7].

A diagram of the gas system is shown in Fig. 4. The vacuum pump evacuated the test cell and interconnecting tubing. Insulator gas was introduced from the gas bottle via the pressure regulator. Gas pressure in the test cell was monitored by a calibrated Wallace and Tiernan model FA160410 precision gauge. When a test was complete, the vacuum pump removed the used gas by venting it outside and replacing it with air through the gas drying unit. For tests requiring a wet gas, water vapor at the correct partial pressure was introduced into the evacuated test cell; then the fill was completed using dry gas.
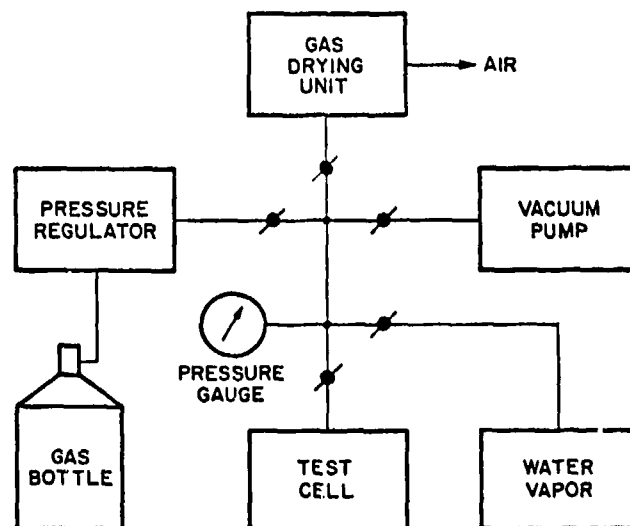

Fig. 4 - Block diagram of gas system

MEASUREMENTS

The endurance function curves generated by the measurements showed some of the basic characteristics needed to analyze sonar transducer reliability. Among these were the endurance time decrease with increasing voltage stress magnitude and function variations with specific gas changes. Also, in addition to corona, a surface conduction mechanism was observed that may be useful for developing a nondestructive test to evaluate the voltage-withstand capability of transducers.

Test Results

The curves of Fig. 5 show the endurance function of 0.635-cm (0.25-in.) thickness PZT in the various insulator gases. The time axis is the length of time to the failure event at the different voltage exposure levels. Each of the functions has three regions of interest: 1) the higher voltage area that is the maximum short-term withstand capability, 2) an intermediate area in which a time-dependent failure mechanism operates, and 3) a lower-voltage area that is usable for long-term operation.
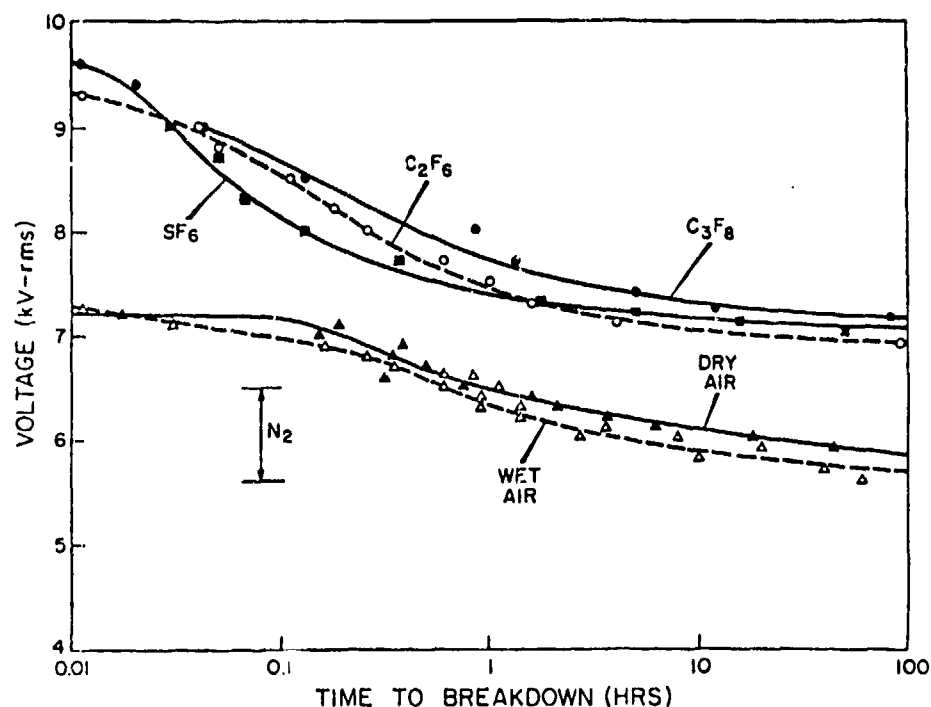

Fig. 5 - Voltage endurance functions for 0.635-cm thickness PZT ceramic in various insulator gases

The time axis may be interpreted as the cumulative exposure
time to high voltage. This effect was demonstrated using several
tests that were stopped before failure and a 1-hour rest given
before the test was completed. In all cases, the cumulative time
of voltage exposure for the interrupted tests was nearly the same
as for uninterrupted tests.

The main implications of the endurance functions of Fig. 5
that apply to sonar transducer design are:

- The long-term voltage level withstand capability of SF_6,
  C_2F_6, and C_3F_8 gases is approximately 20% greater than
  with dry air. This compares to short-term test indications
  that the difference was 60-70% greater [5].

- The intermediate failure mechanism progresses approximately
  two times faster in SF_6 than in C_2F_6 or C_3F_8. This
  failure mechanism progresses more slowly in dry air than
  with any of these three gases.

- Nitrogen gas did not yield a clear-cut endurance function
  but gave upper and lower failure limits as indicated.
  Failure was by arcing through the gas instead of on the
  PZT ceramic surface.

The effect on the endurance function of increasing the PZT
ceramic thickness to 1.27 cm (0.5 in.) is shown in Fig. 6 for the
gases SF_6, dry air, and wet air. The features of the curves of
Fig. 6 are similar to those of Fig. 5, and doubling the ceramic
thickness also approximately doubles the failure voltage level.
The curve shapes also indicate that thick ceramic discs will have
greater endurance to over-voltage transients than will thin discs.

Both Figs. 5 and 6 give an indication of changes to the
curves resulting from the presence of water vapor in air. There is
a scattering of the data points and lowering of the curve by a few
percent. Although complete curves were not obtained, results for
water vapor in SF_6 gas were similar. This is evidence that water
vapor in the insulator gas may cause some reduction of the reliability
of transducers, but the margin of difference is small.

Tests were conducted to determine the effect on the voltage
endurance function with SF_6 gas when there is air contamination or
there is a gas pressure change. The test conditions were an air
concentration fraction of 25% and pressure levels of 50, 101, and
151 kPa. The breakdown voltage at a given time-to-failure increased
about 3% for each 50-kPa pressure increment increase. Air contamination
had almost no effect on the function. Both reduced gas pressure
and air contamination increased the observed corona level, but the
corona did not appear to affect the voltage endurance function.

Voltage Endurance Function

Some investigators [1,8,9] have shown that the endurance function of materials exposed to corona discharges may be fitted to the function

$$[(V-V_e)/V_e]^n \; t = c \qquad (1)$$

where V is the applied voltage in kV, V_e is the corona extinction voltage, n and c are constants, and t is failure time in hours. From Eq. (1), time may be computed from a simple rearrangement.

$$t = c[(V/V_e)-1]^{-n} \qquad (2)$$

The intermediate time-dependent area on the curves of Figs. 5 and 6 may be fitted to this function, but the quantity V_e is replaced by V_a, which is a voltage level asymptote to the curve where t is large. The flattening of the curves in the area with small values of t is due to a different breakdown mechanism and is neglected because it is not significant for transducer lifetime analysis.
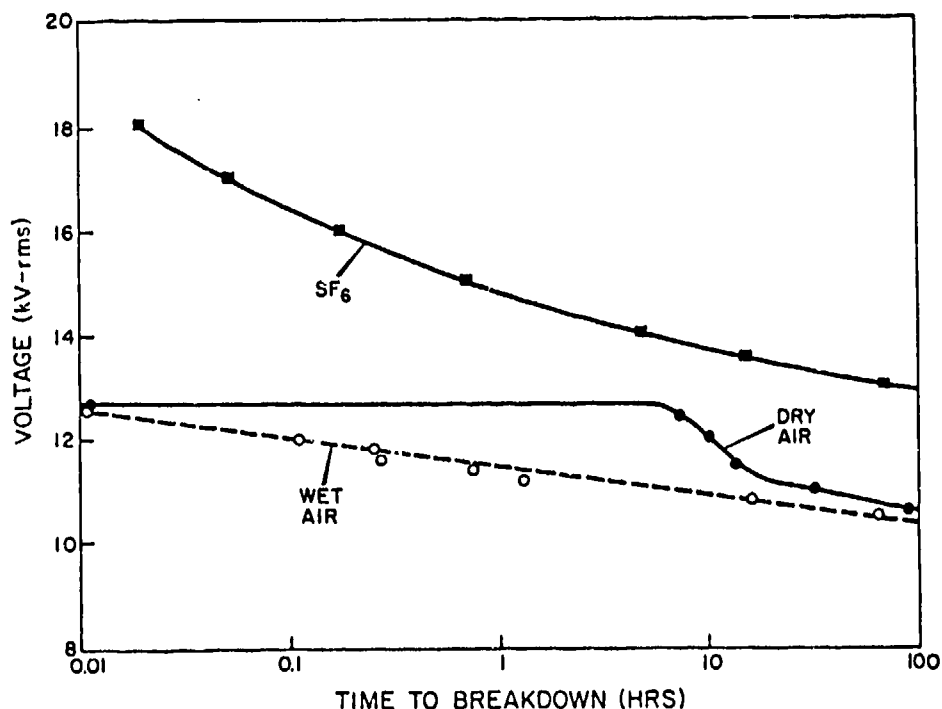

Fig. 6 - Voltage endurance functions for 1.27-cm thickness PZT ceramic in air and SF_6 gases

Table I - Endurance Function Factors With Different Gases

Gas	V_a (kV)	V_1 (kV)	n	c
Dry Air	5.6	6.5	3.6	.0014
Wet Air	5.5	6.3	2.8	.0045
SF_6	7.0	7.4	2.2	.0018
C_2F_6	6.8	7.4	2.1	.0061
C_3F_8	7.0	7.7	2.3	.0050

The endurance function curves with each of the gases shown in Fig. 5 may be computed from the mathematical expression

$$t = c[(V/V_a)-1]^{-n} \qquad (3)$$

using the quantities given in Table I. The values for c in each case are evaluated with the formula

$$c = [(V_1/V_a)-1]^n \qquad (4)$$

in which V_1 is the voltage level of the function where t = 1 hr.

The curve in Fig. 6 for SF_6 may be expressed as:

$$t = .001 [(V/11)-1]^{-6.5}. \qquad (5)$$

The data for dry air and wet air in Fig. 6 are not complete enough to evaluate the function, particularly the value for V_a.

Breakdown Mechanism

The approach to arc breakdown can be monitored by observing certain small irregularities on the corona detector indicator. These irregularities increase to a high level before failure occurs and generally give warning that voltage breakdown is imminent. This is an indication of electric current pulses near the peaks of the drive voltage, but with frequency components below the low cutoff of the corona detector. No light or visible glow is associated with the phenomena even though the current is at a relatively high level compared to corona. The normal corona discharge pulses appearing on the corona detector do not increase in magnitude or number in a way that would indicate a correlation of corona activity to breakdown.

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The electrical current pulses at the peaks of the drive voltage
are detected using a current transformer and instrumentation as
shown in Fig. 3. The current waveforms of Figs. 7(a) and 7(b)
illustrate changes in the pulses from the test start to near failure.
Low-frequency components of the 60-Hz current were removed using a
300-Hz high-pass filter. The driving voltage waveform is shown in
Fig. 7(c).
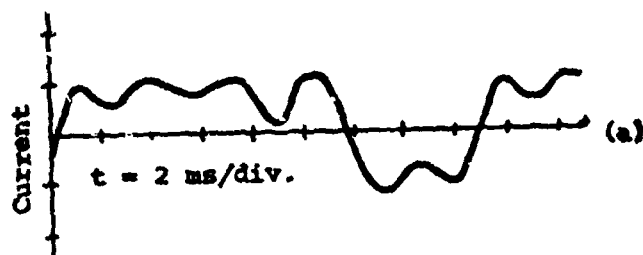
(a)   Current waveform early in test
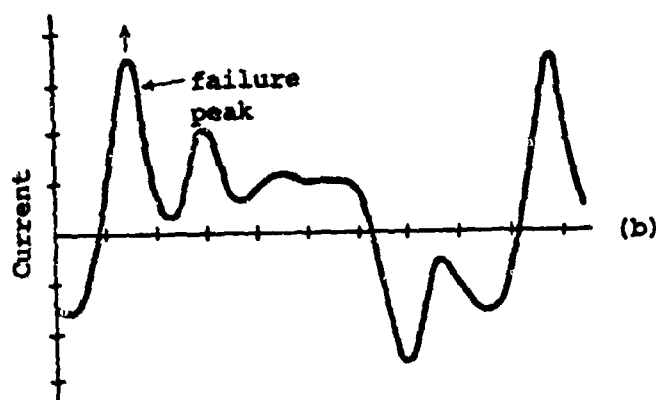
(b)   Current waveform late in test
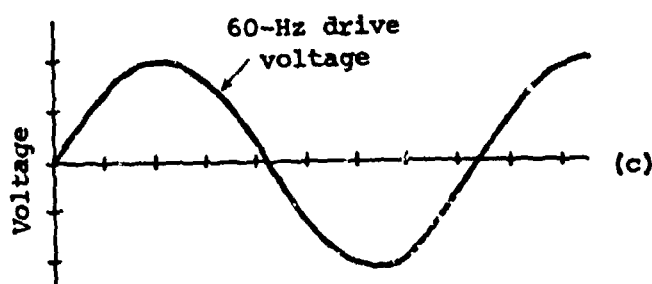
(c)   Test driving voltage waveform

Fig. 7 - Electrical test waveforms

Characteristics of this electrical current pulse phenomena
are:

- The current pulse occurs roughly on the peak of the drive voltage waveform.

- The current flow is probably a surface phenomena because the various insulator gases change the endurance function.

- The pulse progressively increases in amplitude as the ceramic proceeds to breakdown.

- The magnitude of the current pulse is sufficiently large to dissipate 0.5 W and may be localized to *hot spots* on the ceramic surface.

- The current pulse that builds up to failure occurs on the driving voltage peak that is in series aiding the ceramic polarity.

- The predominant frequency component introduced by the pulses on the current waveform is the sixth harmonic (360 Hz) of the driving voltage.

- There is a specific minimum driving voltage at which the current pulses have their inception; for instance with 0.635-cm (0.25-in.) thickness ceramic in dry air, the inception voltage is between 3 and 4 kV.

CONCLUSIONS

This study is intended to evaluate and analyze some of the time-dependent factors associated with sonar transducer reliability. The effectivenss of the study is related to answers to the following specific questions that are asked about electrical breakdown of sonar transducers.

- *Is there a mathematical function that describes voltage endurance and allows prediction of transducer lifetime?*

Equation (3) is the mathematical function showing the basic relation between voltage drive level and time to voltage breakdown. The time-to-breakdown increases as a power function with decreasing voltage levels, approaching V_a as an asymptote. The results presented are representative of the general electrical breakdown phenomena and indicate the mean-time-before-failure factor in the hazard rate reliability function.

The endurance function described indicates that PZT ceramic under carefully controlled conditions may have a usable dielectric strength as high as 780 kV/m (20 V/mil) with dry air the insulator gas. Because experience has indicated that more than 275-390 kV/m (7-10 V/mil) invites failure, careful life testing should be conducted on any transducer designed using the greater voltage stress.

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* *How does the endurance function change if other good*
  insulating gases replace air in the solid/gas interface?

The other good insulating gases tested were SF_6, C_2F_6, and
C_3F_8. The general shape of the endurance function with these gases
was the same as for air. Breakdown for all three of the better
gases in the long-term area was about 20% greater than in dry air,
or approximately 940 kV/m (24 V/mil).

* *Does changing the physical parameters of ceramic thickness*
  and gas pressure affect the endurance function?

There are some differences in the endurance function curves
due to changing the ceramic thickness, but generally the breakdown
voltage is proportional to thickness. Gas pressure did affect
the corona inception voltage, but the failure voltage was changed
only a small amount.

* *If the insulating gas is contaminated with water vapor*
  by premeation, is the endurance function modified?

Water vapor in the insulating gas reduces the breakdown voltage
by a small amount, but it will not account for any substantial
reduction of the reliability of a transducer.

* *Does the general test procedures and specifications for*
  qualifying transducers for high-voltage operation
  measure physical phenomena that can be interpreted in
  terms of transducer reliability?

Reliability is evaluated from measurements of unit time to
failure. The high-voltage breakdown test of ASTM D149-64 and the
corona detection test of ASTM D1868-73 are typical of test
procedures used in transducer specifications. Neither of these
tests provides for applying the voltage stress for a time
duration that will allow for electrical discharge deterioration
effects on the transducer materials. The results of these tests
indicate that a high-voltage test should be about one hour in
length to obtain data that are an indication of transducer
reliability.

* *Are the transducer electrical specifications*
  insufficient, sufficient, or excessive to
  accomplish the goal of reliability?

It is probable that most electrical specifications on dc or
60 Hz test voltages are insufficient. The data suggest that it may
be necessary to derate the permissible transducer drive voltage at
operating frequencies greater than the 60 Hz test. Tested at the
frequency of operation, a transducer should withstand 150% of the

normal drive voltage for several minutes, or 130% of this voltage for about one hour.

A corona inception voltage (CIV) test is basically a measure of the quality of construction in a transducer rather than an indicator of reliability. The main requirement for a CIV test is to assure that corona is not excessive at the voltage level 110-120% of operation.

- *Do the tests identify defective materials and workmanship in the transducer construction?*

The CIV test is useful to identify transducers with defective materials and workmanship such as cracked PZT ceramic, sharp points or electrode edges, or thin air gaps in the insulation material between electrodes. Corona may also form on small diameter wiring. However, it is difficult to demonstrate a correlation between corona discharges and transducer reliability.

- *Do these tests identify all of the electrical phenomena that lead to electrical failure in sonar transducers?*

In sonar transducers, the voltage breakdown event is observed to be associated with a surface conduction phenomena that is detected only indirectly with a corona detector. There are also several different and distinct corona pulse forms visible on the corona detector. The interrelationship of these effects progressing to electrical breakdown is complex, but if corona and surface conduction can be reduced there should be a corresponding improvement in transducer reliability.

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